N91-28197

A WHITE PAPER:

OPERATIONAL EFFICIENCY

NEW APPROACHES TO FUTURE PROPULSION SYSTEMS

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JUNE 1990

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FOREWORD

First, I would like to thank the Program Committee for giving the launch site the opportunity to provide visibility from our experience base back into the technology development process. I feel this is very important if we are to resolve these large deficiencies; they must be made visible.

Until now, our main thrust has been simply getting into and back from space. All criteria has been based on performance parameters, such as ISP, GLOW, T/W, mass fraction, etc. The rocket engine development, because of required long lead, led the process by establishing artificial interfaces for the design and operational control. The engine contract end item specification (CEI) and interface control document (ICD) were used for ease of procurement and development testing and to establish interface requirement for whoever desired its use. The vehicle, therefore, would assume the weight and operational burden of all the systems demanded by the engine. The mission use would determine the vehicle size and the number of engines required. Cost and launch rate were not of concern during the early years.

During the Apollo lunar exploration program, it became apparent that the Apollo vehicle launch operations were consuming a very large part of the agency budget, leaving very little for other scientific work and no new start programs. Therefore, we determined that developing a new vehicle that reused the very expensive vehicle hardware was the answer, ie., the Shuttle vehicle was born with expected large reductions in the cost of delivering a pound to orbit with 60 launches per year. Forty launches at KSC and 20 at WTR per year, but the design did not support this ambitious launch program. Also, the launch operations crew size was nearly the same as for the Apollo vehicle. Where did we fall short in our vision?

KSC initiated a self-examination three year study of cause and effect, led by Bill Dickinson and performed by the Boeing Company. This effort identified the vehicle configuration is the primary driver of this high cost limited launch capability. It also identified the propulsion system as a major discipline driver. Therefore, we initiated a more in-depth study of the causes and effects with the hope of identifying major generic operations concerns that cause the status quo. This present one-year effort has accomplished this, along with identifying alternate concepts that offer major reductions in complexity and manpower intensive operations. Therefore, the next 30 years we can focus on an ambitious space exploration by applying the knowledge gained from this visibility.

By applying the principles of TQM (old fashioned team effort) to Advance Planning, Conceptual Design, Development of Requirements and through the Design Development Process, we can achieve low cost, reliable, timely access to space and an operationally flexible space transfer system.

From our experience, the approach to follow is clear: Develop a simple, reliable, operationally efficient, integrated propulsion system concept that can be used and sized for different missions/vehicles. The concept must be fully integrated to achieve major reduction in propulsion components. This approach will yield major reduction in traditional vehicle support systems. We need to concentrate on the use of LOX/LH2 for all vehicle fluid needs. This combination will provide an environmentally clean operation and will enable a totally integrated propulsion and vehicle power capability, ie., MPS, OMS, RCS, fuel cells, cooling/thermal management and life support systems. Now, what is the propulsion development approach to follow?

First, we must surface the necessary technology needs to allow this ambitious space exploration program to occur. Develop these technology items into projects and follow them through maturity for use. I can't over stress the importance of a thorough maturation program, including flight tests in some cases. We must maximize the use of manpower and facilities. After all, the most valuable resource this country has is its people. We suggest we consider realigning our Government and industry teams and procurement practices to perform productive work and increase operational flexibility. We must discontinue our practice of creating artificial interfaces, unnecessary constraints, to allow fresh creative work to progress. After all, unnecessary constraints are the enemy of the bold. The competitive approach to advance planning and conceptual design is very wasteful; therefore, we suggest the consortium concept be considered. Let's use the competitive approach to providing high quality hardware from at least two sources.

Let us develop a means of measuring operability during our conceptual/design process. The commercial sector compares the use time to the shop maintenance/overhaul time and for them to turn a profit, this ratio must be in favor of use time. Traditionally, we spend large amounts of time preparing for a very short use time. Our conservative leadership is reluctant to make a long term commitment of advancing propulsion operations and give up their comfortable position of accepting the status quo, along with its near term personal or corporate gains. Can we afford to continue using the old patterns (ICD's and CEI's) while the rest of the world takes over the leadership position of space propulsion.

Let us accept the challenge for the future. Don't simply build a new model (an old one with a face lift) and spend 90% of our efforts concentrating on the lift off and ascent extravagance when it should be a routine event. But, instead, let us work together as a team and provide real measurable progress, allowing us to achieve the next frontier! "Routine Access to Space."

Mr. George Wong (Rocketdyne-Canoga Park, CA) will now talk to you about how applying the TQM team process makes a difference. He will share with you his experience this last year and give you an example of how this experience can influence the future of propulsion with focused technology development and the freedom to be creative.

Operationally Efficient Propulsion System

R.E. Rhodes and G.S. Wong

Introduction

Advanced launch systems for the next generation of space transportation systems (1995 to 2010) must deliver large payloads (125,000 to 500,000 lbs) to low earth orbit (LEO) at one tenth of today's cost, or 300 to 400 $/lb of payload. This cost represents an order of magnitude reduction from the Titan unmanned vehicle cost of delivering payload to orbit. To achieve this sizable reduction, the operations cost as well as the engine cost must both be lower than current engine systems. The Advanced Launch System (ALS) is studying advanced engine designs, such as the STME, which has achieved notable reduction in cost. This paper presents the results of a current study wherein another level of cost reduction can be achieved by designing the propulsion module utilizing these advanced engines for enhanced operations efficiency and reduced operations cost.

The operations cost of today's launch systems has become a large fraction of the vehicle recurring cost per flight ranging from 20 to 40% for expendable and reusable vehicles, respectively, shown in Figure 1. The complex operations requirements of current launch vehicles have also limited our ability to achieve routine access to space. Since the rocket engine/propulsion system represents one of the more complex and expensive systems in the launch vehicle, a study was made to identify operations problems (cause and effect concerns) which have driven operations costs to exorbitant levels. This paper presents the importance and a description of the major operations problems encountered in today's launch vehicles and how these problems have adversely affected our ability to achieve serviceability, reliability and operability. It also emphasizes the need to recognize and understand the operations problems and the effort that must be made to avoid them in future designs, i.e. applying the "lessons learned". It describes how the operations requirements for accessibility, maintainability and operability are allowed to start with the initial engine design to drive the design requirements. This has never been done before and this has been part of the reason today for the high cost vehicle launch systems and for the large launch processing cost and time. Finally, the paper presents an example whereby a propulsion concept that "integrates" the engine system not only results in a propulsion system that is more operationally efficient, with sizeable reduction in operations cost, but also results in a propulsion system that is simpler, more reliable, more operable and has lower cost than a conventional unintegrated engine system.

Current Operations Problems

Processing flight hardware for launch has been a very tedious and time consuming task requiring large numbers of people operating sophisticated ground support equipment (GSE) to verify flight system readiness. For each subsystem assembled with the major vehicle element, such as the Orbiter, comes the requirements for total system checkout prior to certification for flight. This process has been quite complex and involves numerous other systems during the checkout.

For Example, to support checkout of a main engine, the main propulsion system, electrical power and distribution system, hydraulic system, instrumentation system, flight control system, avionics system, environmental system and the purge, vent and drain systems must all be activated to support the engine checkout. The checkout itself also requires highly trained and skilled personnel at the vehicle, in the firing room and at the GSE supplying the required commodities like gases, hydraulics, power, etc. All these activities are in turn dependent on test conductors, quality control, safety, GSE engineering, etc. to accomplish a successful test. As many of these activities are "hands-on" and serial in nature further complicates the checkout process. The ground support system providing services and commodities also must be verified that every system is available and certified to support the test. It is therefore not surprising that operations support for launch system checkout is complex, manpower intensive, time consuming and costly and a launch system that consists of many separate, independent systems simply exacerbates this problem.

A typical illustration of the technical disciplines and operations support required for system checkout is depicted in Figure 2. An illustration of the large infrastructure of logistics, supplies, equipment and facilities to support the system checkout is shown in Figure 3. Every different commodity required on the vehicle adds another tentacle to the operations support structure. For example, the requirement for Helium gas, no matter how small the amount, dictates the need for additional facilities, GSE, logistics, transportation, etc. to insure that the gas is at the vehicle processing site when needed.

Several recent studies on launch site experience have been made to identify operations problems that have driven our operations cost to exorbitant levels and have severely restricted our ability to achieve routine access to space. The Shuttle Ground Operations Efficiencies/Technologies Study (SGOE/T)[1] investigated the operations requirements of the entire vehicle including payload and the more recent "Operationally Efficient Propulsion System Study (OEPSS)[2] focused on the operations requirements of the total propulsion system that included: the propellant tankage, fluid systems, structure, engines and controls. Both studies have concluded that current operational requirements are driven by (1) systems that are not readily serviceable; (2) too many people are required; (3) too much time is needed for processing; (4) complex support facilities are needed; (5) serial operations are required; (6) hazardous operations are involved; (7) and too many commodities and grades of commodity are used.

The OEPSS study has also identified some serious major problems that have plagued our launch operations requirements and have compromised our launch capability. Figure 4 contains a list of these operations problems and the main propulsion system contained within a closed aft compartment was found to have the most widespread impact on ground operations. Other operations problems that drive operations support include the hydraulic systems, gimbal systems, turbopumps, inert gas purge, excessive number of components, many artificial interfaces and the lack of hardware integration. Some of these are described below.

Closed Aft Compartment

An enclosed engine compartment at the boat-tail of the launch vehicle causes numerous ground operations problems because leakage of hazardous fluids can be confined, access is restricted and complex GSE is required. Confinement of potential propellant leaks is a Criticality-1 failure. A closed compartment will require an inert gas purge system, a sophisticated hazardous gas detection system and a personnel environmental control system. These systems in turn will require vehicle - ground interfaces and ground support equipment, all of which in turn will require separate specialized personnel to provide maintenance, checkout and servicing. Moreover, inert gas purge poses personnel safety issues.

Hydraulic System

A hydraulic system represents another fluid distribution system that must be processed and maintained for flight operations. This involves distribution system leak checks, long periods of circulation for de-aeration/filtering operations associated with fluid sampling and analysis, and functional check of all control systems. In order to process the flight system, a ground support system consisting of all the basic hydraulic distribution system elements must be duplicated to simulate pressure for the flight system checkout. The same operations and maintenance requirements are also required for the ground system.

The auxiliary power units to drive the hydraulic pumps represent an additional support system of prime mover, pumps, gearboxes, lube oil system, cooling system, instrumentation, distribution system, etc. which will require additional maintenance and checkout; and if a hypergolic-fueled auxiliary power unit is used, this will drive the need for a whole separate operations support infrastructure that dictates serial operations and the need for specially certified personnel to work in self-contained atmospheric protective ensemble (SCAPE) for fueling operations.

Lack of Hardware Integration

A launch system that contains numerous separate, stand-alone systems proportionally drives up the number of duplicate components and interfaces. This in turn exponentially drives up the complexity and the operational support requirements. Each stand-alone system promotes artificial interfaces and each interface represents another "break point" in the system that must be checked and verified should the connection be broken. Each fluid interface represents a potential leak point requiring special attention for disassembly, reassembly and leak checks. Separating fluid connections leads to potential sealing surface damage, which in turn requires repair of the sealing surface and, if severe, requires a line changeout. It is not uncommon in a critical system containing helium, hydrogen or oxygen to replace seals more than once to ensure an acceptable leak-free joint. An example of separate stand-alone systems is a launch vehicle propulsion system using multiple autonomous engines. The propulsion system will have as many duplicate propellant lines, valves, thrust chambers, turbopumps, control/avionics, heat exchangers, pneumatic control assembly, etc and interfaces as there are engines.

Systems carrying fluids such as hydrogen and oxygen necessarily dictate the use of sophisticated, highly sensitive, operations intensive leak detection devices, such as mass spectrometers, to verify the integrity of the seal. This requirement drives up the time required to leak check a joint considerably. High helium content in the surrounding area can cause leak checks to be delayed until the background is reduced or add time to the operation by having to encapsulate each joint that is checked. Leak checking many joints has led to time-consuming serial operations impacting the total system checkout.

In view of current experience, it is abundantly clear that operational complexity stems from design. The operational support of current flight systems was never fully understood nor the impact on launch processing was fully appreciated during design. In order to achieve operational efficiency, the principle of Total Quality Management (TQM) must be applied to ground operations as it is being applied to product quality, that is quality cannot be inspected into the product, it must be designed into it. Therefore, operations must not simply support the design it must change and drive the design at its conceptual beginning toward greater simplicity and greater operability. This imperative approach is illustrated in the design/build/operations cycle shown in Figure 5.

Operationally Efficient Propulsion System

To achieve operational efficiency for a flight system the design must be simplified to reduce operations required to support the system. An example will be used here to illustrate how the "lessons learned" from current operations experience (Figure 4) are used to drive the design of a propulsion system concept for a heavy lift launch vehicle, such as the Advanced Launch System (ALS). The example will describe how the design can be simplified by "integrating" the multiple engines to eliminate as many components and interfaces as possible while maintaining the required thrust and control of the vehicle.

The baseline ALS vehicle shown in Figure 6 will be used as a reference vehicle for comparing a traditional approach to designing a conventional propulsion system vis-a-vis with an integrated approach to designing an operationally efficient propulsion system. The ALS vehicle shown consist of a core vehicle and a side-mounted booster with a gross lift-off weight (GLOW) of 3,500,000 lbs. and a payload capability of 120,000 lbs. to low earth orbit (LEO). Both the booster and core vehicles are 30 ft. in diameter and use 580,000 lbs. thrust (vac) O_2/H_2 STME engines. The booster and core utilize 7-engines and 3-engines, respectively, for their propulsion systems.

Summary and Conclusion

Today's launch systems have resulted in high operations cost and low flight rates. The complex systems have been found to be the cause for the inordinate time and manpower needed to meet ground operations requirements and for our inability to achieve routine access to space. The complex propulsion system for our current launch systems has been a major part of this problem. In order for future advanced launch vehicles, such as the ALS, to deliver payload to orbit (LEO) at lower cost and at higher flight rates, the design of the launch system, and particularly the propulsion system, must be greatly simplified and made more operationally efficient. The results of the current study ~~summarized in Figure 18~~ have shown that by utilizing an unconventional "integrated" design approach, a low cost, operationally efficient propulsion system design can be achieved. Based on the study results, the following conclusions are made:

(1) To achieve an operationally efficient, low cost propulsion design, operations cost drivers must drive the design at the inception of concept. A design that initially ignores operations problems can not subsequently be made truly operationally efficient.

(2) Propulsion system design for future launch systems can be made simpler and require less operations support by reducing the number of components and interfaces and by integrating the system functions. This is achieved by departing from the conventional engine design approach and by using the "integrated-component" design approach described.

(3) The integrated propulsion module engine as an alternative propulsion concept for the ALS illustrates the following point: given a propulsion system design using multiple stand-alone, autonomous engines, an integrated design of the same system will always yield an equivalent system that will have substantially higher reliability and lower unit cost.

(4) An integrated propulsion design is tractable[3] and can use existing or current ALS technology and does not require new technology (enabling).

(5) An integrated design approach results in a propulsion design that is simpler, more reliable, more operable, lower unit cost than a conventional design and, therefore, eminently meets the ALS requirements for robustness, reliability, operability, low cost and the ability to achieve routine access to space.

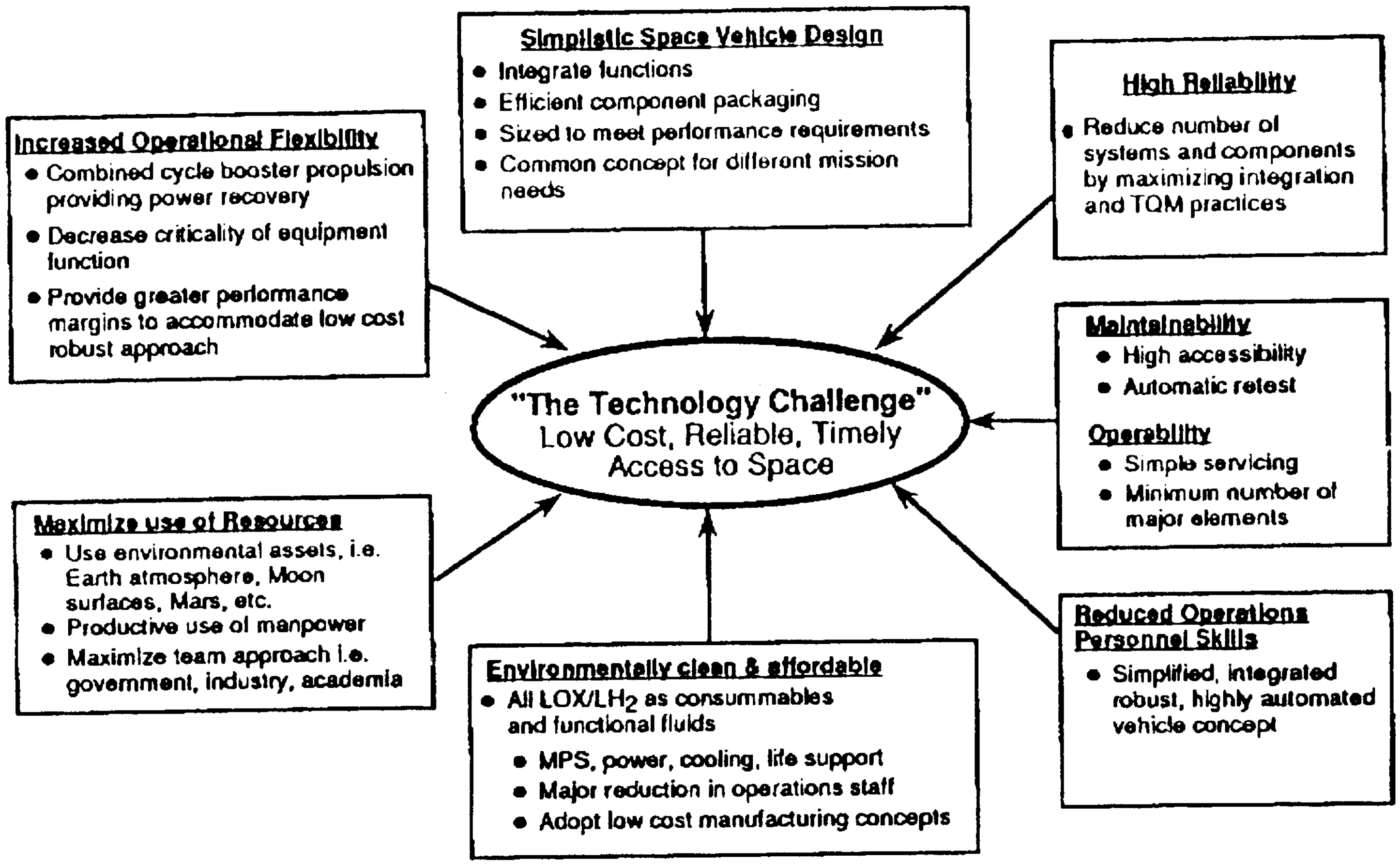
References

1. "Shuttle Ground Operations Efficiencies/Technology Study" (SGOE/T), NASA/KSC Contract NAS10-11344, A.L. Scholz, Boeing Aerospace Operations, 4 May 1989

2. "Operationally Efficient Propulsion System Study" (OEPSS), NASA/KSC Contract NAS10-11568, G.S. Wong, Rocketdyne Division, Rockwell International, RI/RD90-149 (to be issued), 1990

3. "A New Look at Chemical Rocket Propulsion System Configurations for Space - Stage Transport Systems", W.J.D. Escher, Propulsion, Power and Energy Division, NASA Headquarters (informal discussion paper) March 1990

FUTURE PROPULSION DEVELOPMENT



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PROPULSION SYSTEM FOR ALS

- **Defined as a totally "integrated" system of components and subsystems to provide vehicle thrust and control**
  - Tankage
  - Fluid Systems
  - Structure
  - Thrust Chamber(s)
  - Turbopump(s)
  - Controls

- **Use a "minimum" of components and subsystems to meet the functions of the propulsion system**
  - Simple
  - Reliable
  - Robust
  - Operationally efficient

- **Achieve lowest possible cost by applying TQM to propulsion system development process**
  - Design/Build/Operate

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Figure 1

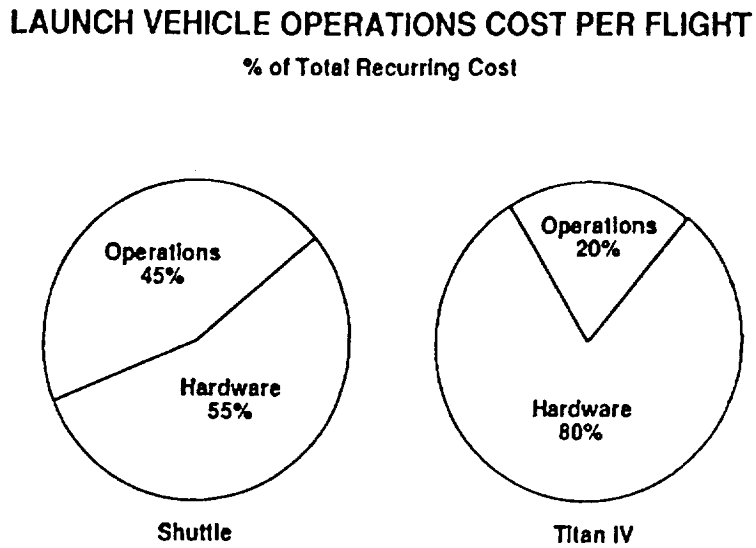

Figure 2

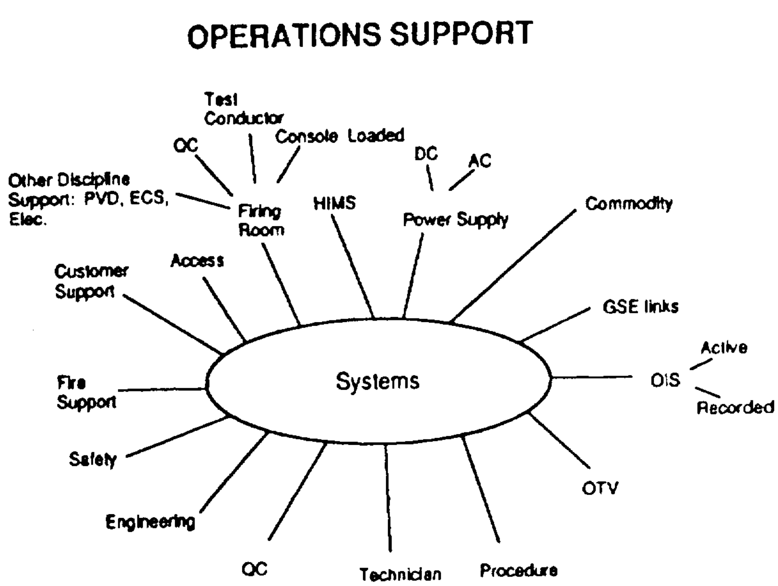

Figure 3

OPERATIONS SUPPORT STRUCTURE

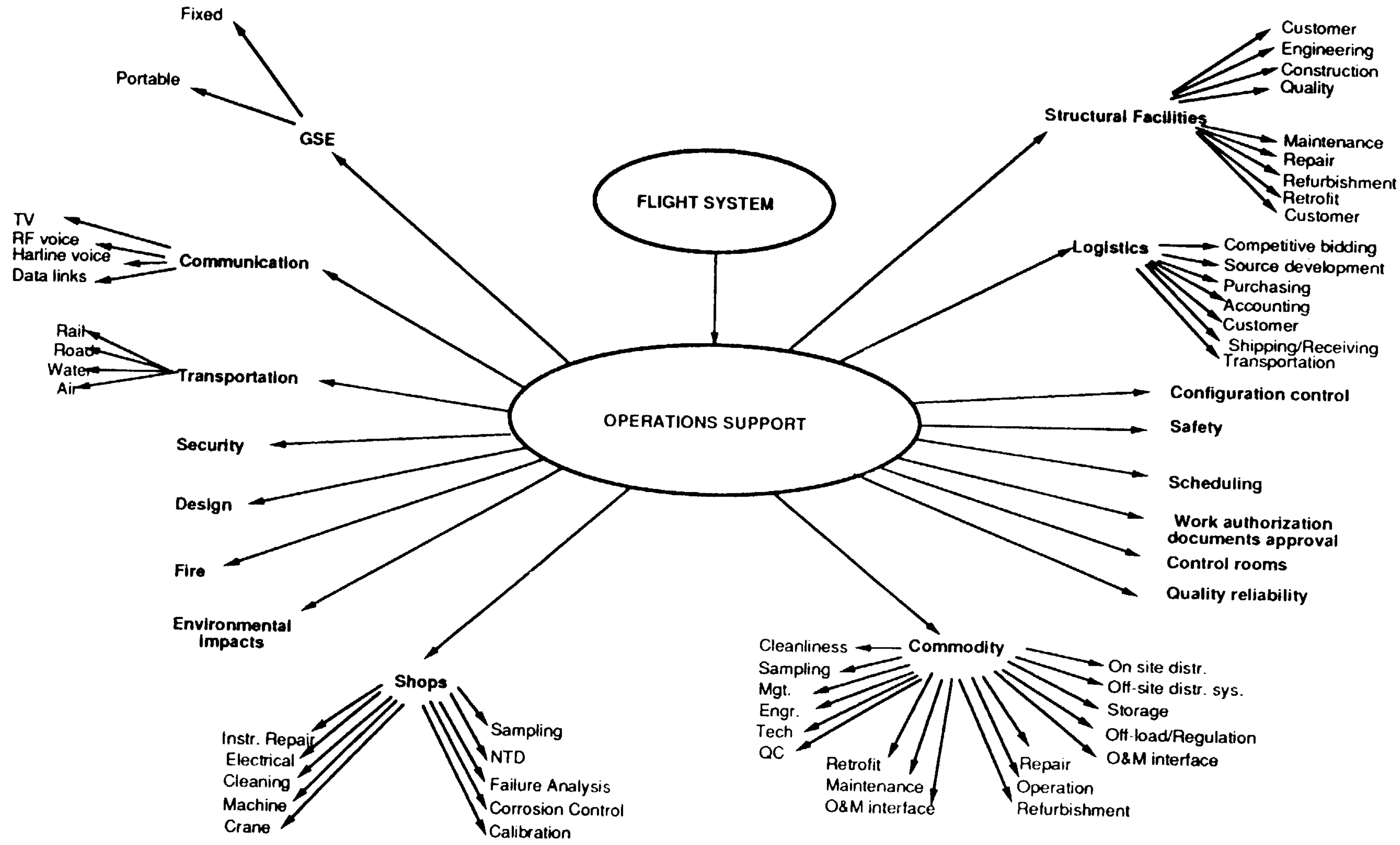

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Figure 4

OPERATIONS PROBLEMS CAUSE AND EFFECTS

No.		No.	
1	Closed aft compartments	14	Ordnance Operations
2	Hydraulic system for valve actuators and TVC	15	Retractable T-O umbilical carrier plates
3	Ocean recovery and refurbishment	16	Pressurization systems
4	Multiple propellants	17	Inert gas purging requirements
5	Hypergolic propellant safety	18	Numerous interfaces
6	Accessibility	19	Helium spin start
7	Sophisticated heat shielding	20	Liquid oxygen tank forward design (propellant system geometry)
8	Excessive components/subsystem interfaces	21	Preconditioning system
9	Lack of hardware integration	22	Expensive commodity usage - helium
10	Separate OMS and RCS	23	Lack of hardware commonality
11	Pneumatic system for valve actuators	24	Contamination
12	Gimbal system requirements	25	Side-mounted booster launch vehicles (multiple stage element propulsion systems)
13	High maintenance turbopumps - recoverable propulsion system		

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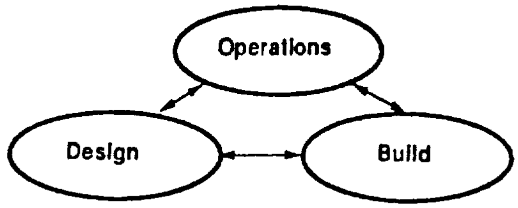
Figure 5

TOTAL QUALITY MANAGEMENT (TQM)

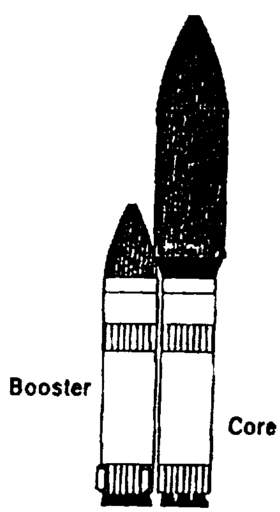
For Total Propulsion System



OEPSS

Figure 6

BASELINE ALS VEHICLE



• Payload	120,000 lbs (LEO)
• GLOW	3,500,000 lbs
• Thrust/weight	1.30
• Booster vehicle	150' x 30' dia.
• Core vehicle	280' x 30' dia.
• Booster engines	7
• Core engines	3
• Engine thrust (vac)	580,000 lbs (STME)

Figure 7

CONVENTIONAL BOOSTER PROPULSION SYSTEM
7 - ENGINE

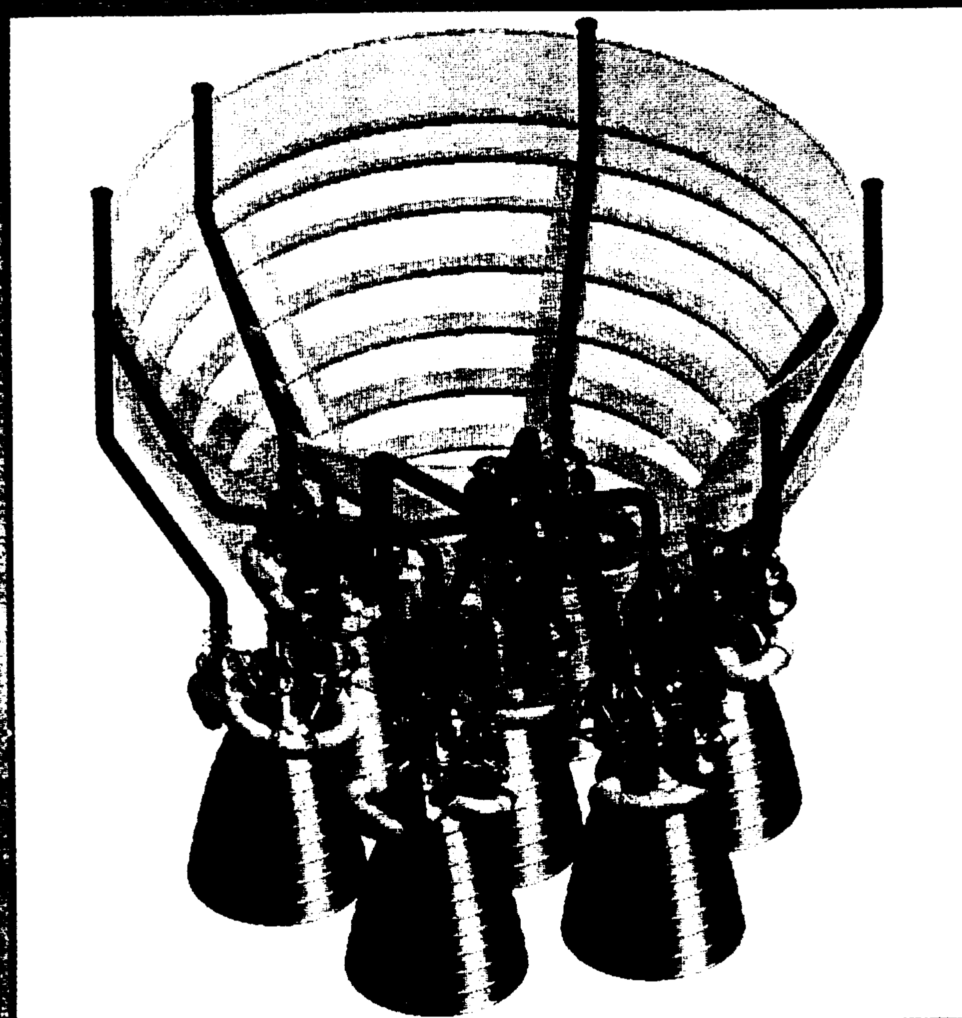


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Figure 8

INTEGRATED BOOSTER PROPULSION MODULE – ENGINE

8 – THRUST CHAMBERS

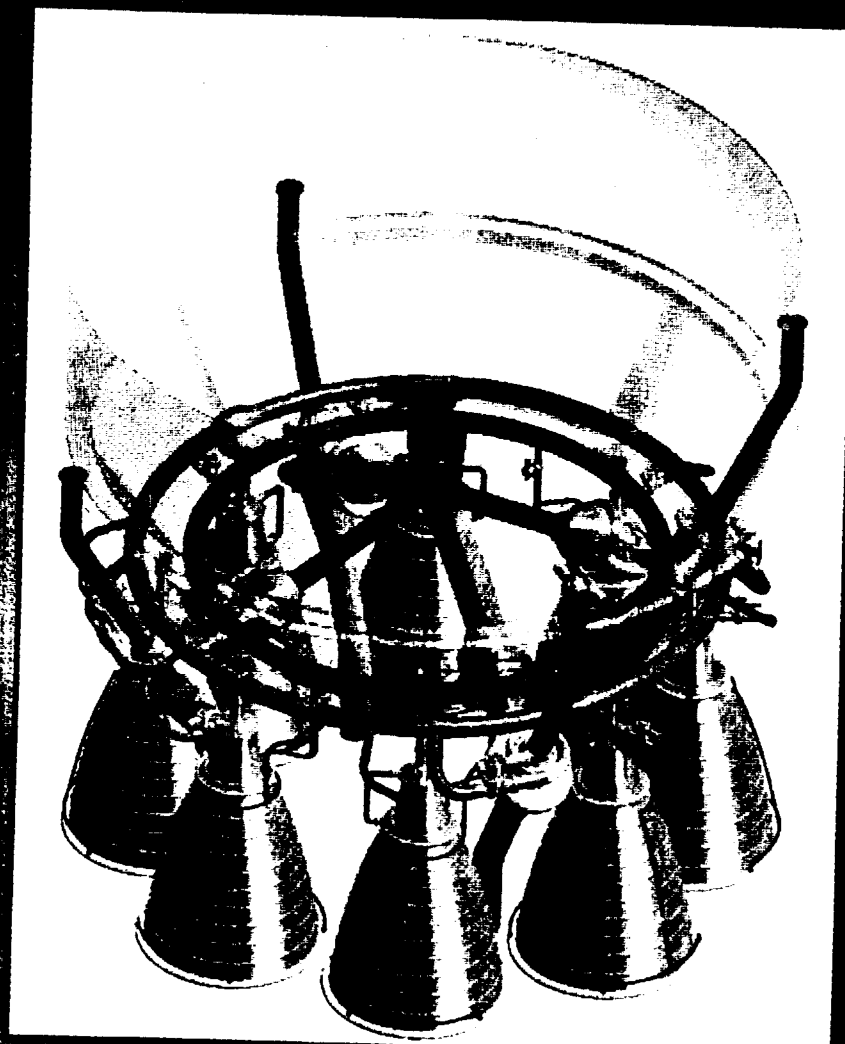

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Figure 9

FULLY INTEGRATED PROPULSION MODULE

- **Single He-pressurization system***
- **Single LOX-pressurization system* (HX)**
- **Single control system***
- **Torus propellant manifold allows 50% reduction of**
  - Turbopumps
  - Propellant inlet lines
  - Gas generators
- **Torus manifold provides "engine-out" capability**
  - Thrust chamber-out
  - Turbopump-out

*Redundancy provided in propulsion module

Figure 10

"ROBUST ENGINE AND ENGINE OUT" CAPABILITY

- **Thrust chamber out capability**
  - Thrust chamber 85% ⟶ 100% Nom. Oper.
  - Turbopumps 67%
- **Turbopump out capability**
  - Turbopumps 67% ⟶ 100% Nom. Oper.
  - Thrust chamber 85%

Figure 11

ROBUST TURBOPUMP DESIGN

- **Design margin**
- **Operating margin**

Booster	7-engine (7-T/P)	8-engine (4-T/P)	
	Des. RPM (100%)	Des. RPM (100%)	Oper. RPM (67%)
LH2-Turbopump	26,000	18,600	12,500
LO2-Turbopump	10,000	7,100	4,800

Figure 12

SUMMARY OF RESULTS

- **Integrated propulsion module vs. conventional propulsion system**

Factor	Fully Integrated	Conventional
• Higher reliability	0.993	0.987
T/C and T/P out	0.999	-----
• Lower engine (T/C) cost, $M	1.83	2.67
• Less number of parts	111	169
• Lower potential weight, lbs.	76,058	87,340
• Lower operations cost, %	-35 to -60	-----

Figure 13

OPERATIONS CONCERNS RESOLVED BY TECHNOLOGY

OEPSS Concerns: ~~1~~ ~~2~~ ~~3~~ ~~4~~ ~~5~~ ~~6~~ ~~7~~ ~~8~~ ~~9~~ ~~10~~ ~~11~~ ~~12~~ ~~13~~ 14 ~~15~~ ~~16~~ ~~17~~ ~~18~~ ~~19~~ ~~20~~ ~~21~~ ~~22~~ ~~23~~ ~~24~~ 25

Technology	OEPSS Concerns Addressed
• No purge pump seals	8 17 18 22
• No purge combustion chamber (start-shutdown)	8 17 18 21 22
• Oxidizer-rich turbine, LOX turbopump	8 13 17 22
• Hermetically sealed inert engine and tanks (prelaunch)	8 17 18 21 22 24
• Combined O_2/H_2 MPS, OMS, RCS, fuel cell, thermal control systems	4 5 8 9 10 24
• Flash boiling tank pressurization	8 9 16 18 24
• Low NPSH pumps	13 16 19 21
• Large flow range pumps	8 13 19 21
• Differential throttling	2 7 8 12
• Electric Motor Actuator (EMA)	2 6 9 11 12 15 18 24
• No leakage mechanical joints	1 2 3 5 8 11 16 17 18 21
• Automated, self-diagnostic, condition monitoring system	1 6 11 12 13 15 21 24
• Integrated modularized propulsion module concept	1 2 3 6 7 8 9 11 12 13 18 19 21 22 23 24
• Anti-geyser, LOX tank aft propulsion concept	9 19 20 21
• Rocket engine, air augmented afterburning concept	3 9 16 17

Figure 14

OPERATIONS TECHNOLOGY APPLICATION

Technology	Vehicle Systems						
	STS	Sh-C	LRB	ELV	ALS	Sh-II	Space
• No purge pump seals			x		x	x	x
• No purge combustion chamber (start-shutdown)			x	x	x		x
• Oxidizer-rich turbine, LOX turbopump			x		x	x	x
• Hermetically sealed inert engine and tanks (prelaunch)			x		x		
• Combined O_2/H_2 MPS, OMS, RCS, fuel cell, thermal control systems		x			x	x	x
• Flash boiling tank pressurization			x		x	x	x
• Zero - NPSH pumps			x	x	x	x	x
• Large flow range pumps			x		x	x	x
• Differential throttling					x		
• Electric Motor Actuator (EMA)	x	x	x	x	x	x	x
• No leakage mechanical joints			x	x	x		x
• Automated self-diagnostic condition monitoring system	x	x	x	x	x	x	x
• Integrated modularized propulsion module concept		x	x		x	x	x
• Anti-geyser, LOX tank aft propulsion concept			x		x	x	
• Rocket engine, air augmented afterburning concept			x		x	x	

Figure 15

CONCLUSION

- **Operations efficiency requirements must start with the initial system design**
- **Operations efficiency to reduce cost must drive the system design in a TQM team environment**
    - Design / build / operate
- **The integrated propulsion module engine is only one example where:**
    - The opportunities for higher operational efficiencies were more fully explored
    - The measurable gains in operational efficiency were identified
- **Other propulsion concepts exist for which the possibilities of greater operational efficiencies have not been fully explored**

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